

## Physical and Wind Properties of [WC] Stars

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**Abstract.** We review the properties of carbon-sequence ([WC]) Wolf-Rayet central stars of planetary nebulae (CSPNe). Differences between the subtype distribution of [WC] stars and their massive WC cousins are discussed. We conclude that [WO]-type differ from early-type [WC] stars as a result of weaker stellar winds due to high surface gravities, and that late- and early-type [WC] and [WO] stars generally span a similar range in abundances,  $X(\text{He}) \sim X(\text{C}) \gg X(\text{O})$ , consistent with a late thermal pulse, and likely progenitors to PG1159 stars.

### 1. Introduction

This review discusses the properties of the small fraction of central stars of Planetary Nebulae (CSPNe) which share a spectroscopic appearance with massive, carbon-sequence (WC-type) Wolf-Rayet stars. Massive WC stars are the chemically evolved descendents of initially very massive O stars ( $M_{\text{init}} \geq 25M_{\odot}$ ) exhibiting the C and O products of core helium burning, plus a unique emission line spectral appearance due to fast, dense stellar wind outflows. Such stars are young, with ages of only a few Myr of which several hundred cases are known within the Milky Way, supplemented by thousands more known in external star-forming galaxies (Crowther 2007; Hamann these proc.).

CSPNe possessing a similar spectral morphology to WC stars are denoted [WC] and are at a post-Asymptotic Giant Branch (AGB) phase in the late stages of evolution of low or intermediate mass stars ( $M_{\text{init}} \sim 1 - 5M_{\odot}$ ?) with only a few dozen examples known in the Milky Way plus a handful in the Magellanic Clouds. With respect to normal H-rich CSPNe, the unusual surface chemical composition of [WC] stars apparently results from a late thermal pulse (LTP), causing a H-deficient surface, and likely connection with other H-deficient stars, most notably PG1159 stars (Werner et al. these proc.)

### 2. Spectral classification

Visual spectral classification of WR stars is based on emission line strengths follows the nomenclature introduced by C.S. Beals and H.H. Plaskett for nitrogen-rich (WN) and carbon-rich (WC) stars, later updated by Smith (1968). An oxygen-rich (WO) subclass was introduced by Barlow & Hummer (1982). The most recent unified scheme spans WC4 to WC11, and WO1 to WO4, based upon the relative strengths of C III-IV and O V-VI and C IV, respectively (Crowther, De Marco, & Barlow 1998). It is well known that the subtype distribution of

massive WC and WO stars differs from CSPNe, in the sense that the Milky Way is dominated by intermediate WC7 $\pm$ 2 subtypes, while CSPNe peak at high and low ionization, i.e. [WO] and WC9–10. In addition, WC subtype distributions depend upon their host galaxy metallicity, with WC4 subtypes dominant in the metal-poor LMC. These differences are illustrated in Fig. 1, drawn from Crowther (2007) for massive WC stars, and the CSPNe catalogue<sup>1</sup>, except for updates from Crowther et al. (1998), Acker & Neiner (2003). The latter classification scheme is specifically applied to just CSPNe, so caution has to be used when inter-comparing [WC] and WC subtype distributions. Galactic bulge [WC]-type CSPNe have been omitted due to difficulties with obtaining robust spectral classifications, in the sense that high dust extinctions hinder observations in the blue for the diagnostic O VI 3811-34 doublet.

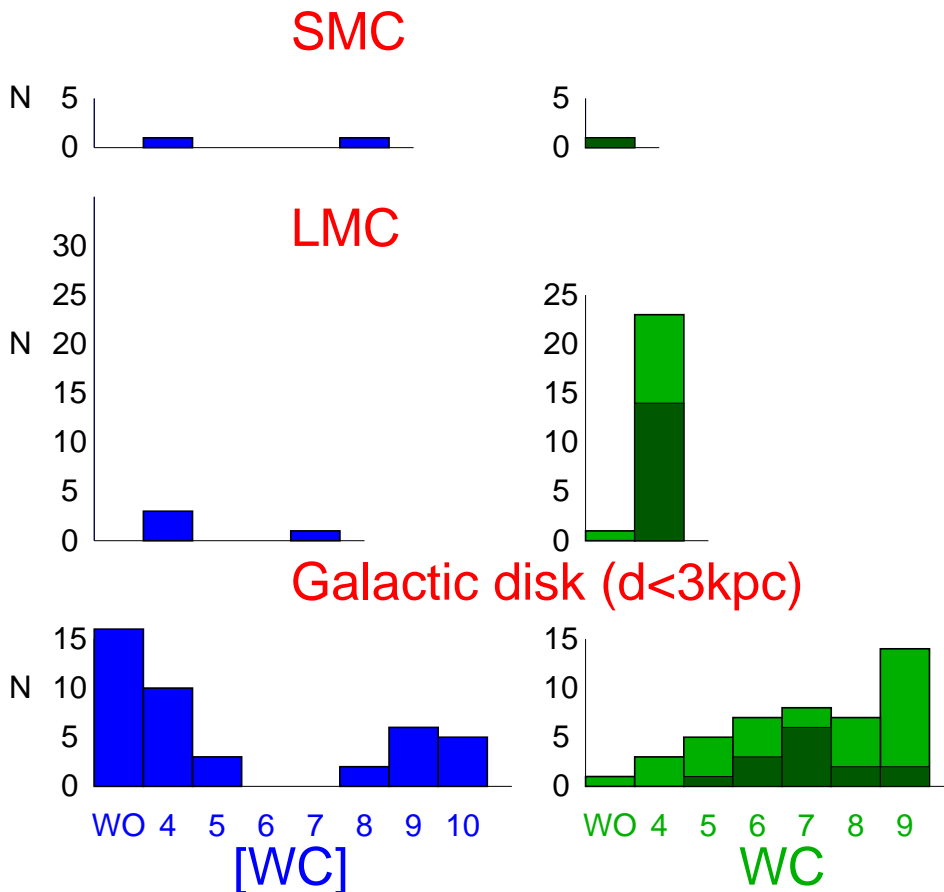


Figure 1. Differences in spectral subtype distribution between massive WC and WO stars in the Solar neighbourhood ( $\leq 3\text{kpc}$ ) plus Magellanic Clouds from Crowther (2007), and WR-type CSPN in the Galactic disk, drawn from the CSPNe catalogue except for updates from Crowther et al. (1998), Acker & Neiner (2003). We have excluded weak emission line stars and hybrid [WO]-PG1159 stars from these statistics

<sup>1</sup> <http://www.arm.ac.uk/~csj/research/catalogue/wccatalog.html>

Regardless of classification issues, it is apparent that some WC-type stars are morphologically identical to [WC] stars, e.g. the comparison between Campbell’s star BD+30° 3639 and HD 164270 by Smith & Aller (1971). In general, [WC] stars possess lower wind velocities, although this is not a defining characteristic. Indeed, the only defining characteristic amongst Milky Way stars is the presence of a bright nebula for [WC] stars.

The [WO] sequence stars overlap with PG1159 stars (Smith & Aller 1969) in the sense that the latter often shows weak O VI 3811-34 emission. Intermediate [WO]-PG1159 stars include NGC 2371 and Abell 78. Beyond [WC], [WO] and PG1159 stars, a number of emission line CSPNe have been grouped together as ‘weak emission line stars’ (wels), although this represents a heterogeneous group, often dictated to by the properties of the nebula. For example, a very strong nebular continuum might cause a genuine [WO] star to be mis-labelled as a weak emission line CSPNe. Overall, care should be taken to distinguish between the various flavours of emission line CSPNe, since some more closely resemble Of stars (e.g. IRAS 21282+5050, Crowther et al. 1998) than [WC] stars.

### 3. Physical properties

Our interpretation of hot, luminous stars via radiative transfer codes is hindered with respect to normal stars by several effects. First, the routine assumption of LTE breaks down for high-temperature stars. In non-LTE, the determination of populations uses rates which are functions of the radiation field, itself a function of the populations. Consequently, it is necessary to solve for the radiation field and populations iteratively. Second, the problem of accounting for the effect of millions of spectral lines upon the emergent atmospheric structure and emergent spectrum – known as line blanketing – remains challenging for stars in which spherical, rather than plane-parallel, geometry must be assumed due to stellar winds, since the scale height of their atmospheres is not negligible with respect to their stellar radii. The combination of non-LTE, line blanketing (and availability of atomic data thereof), and spherical geometry has prevented the routine analysis of such stars until recently.

Specifically for Wolf-Rayet stars, radiative transfer is generally solved in the co-moving frame, using either the CMFGEN (Hillier & Miller 1998) and PoWR (Gräfener, Koesterke, & Hamann 2002) codes. In general, the majority of published [WC] studies have employed earlier non-blanketed versions of these codes, applied to late-type [WC] stars (Leuenhagen, Hamann, & Jeffrey 1996; Leuenhagen & Hamann 1998; De Marco & Crowther 1998) and early-type [WC] and [WO] stars (Koesterke & Hamann 1997ab).

Stellar temperatures for [WC] stars are difficult to characterize, because their geometric extension is comparable with their stellar radii. Atmospheric models are typically parameterized by the radius of the inner boundary  $R_*$  at high Rosseland optical depth  $\tau_{\text{Ross}}(\sim 10)$ . However, only the optically thin part of the atmosphere is seen by the observer. The measurement of  $R_*$  depends upon the assumption that the same velocity law holds for the visible (optically thin) and the invisible (optically thick) part of the atmosphere.

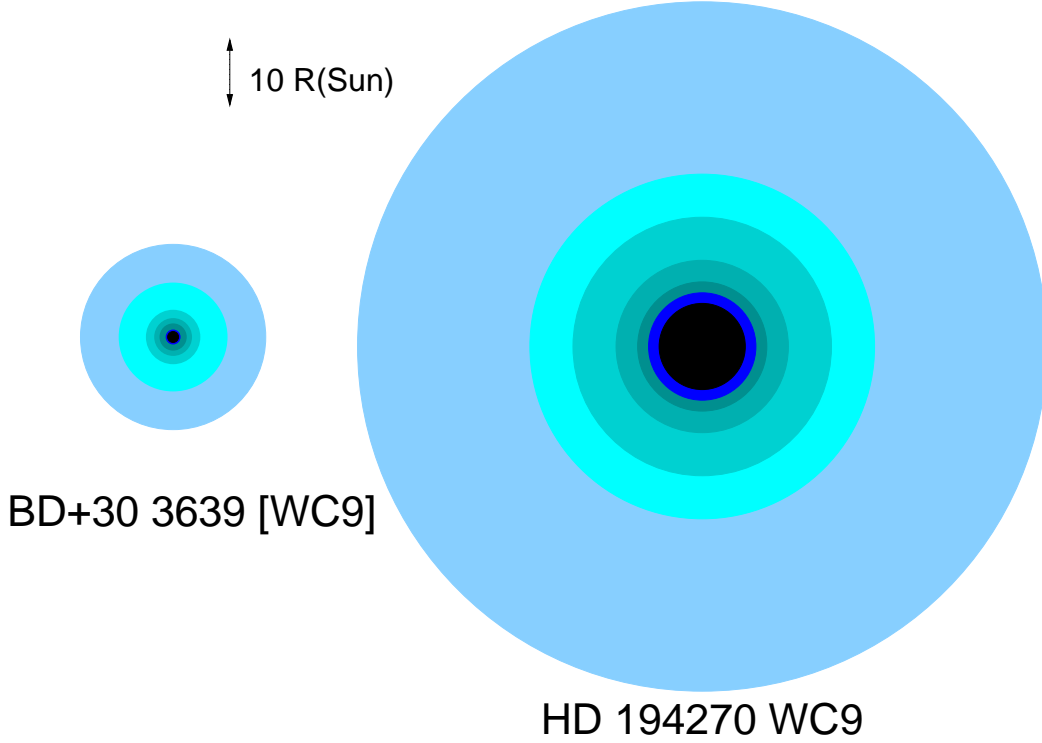


Figure 2. Quantitative comparison between physical radii of the massive WC9 star HD 164270 and the [WC9]-type CSPNe BD+30° 3639. Circles, from inner to outer, relate to  $R_*$ ,  $R_{2/3}$ , followed by the stellar wind at  $n_e = 10^{13}, 10^{12.5}, 10^{12}, 10^{11.5}, 10^{11} \text{ cm}^{-3}$ . Parameters taken from Crowther et al. (2006), confirming the qualitative result of Smith & Aller (1971).

The optical continuum radiation originates from a ‘photosphere’ where  $\tau_{\text{Ross}} \sim 2/3$ . Typical [WC] winds have reached a significant fraction of their terminal velocity before they become optically thin in the continuum.  $R_{2/3}$ , the radius at  $\tau_{\text{Ross}} = 2/3$  lies at highly supersonic velocities, well beyond the hydrostatic domain. In some weak-lined, [WO] stars, this is not strictly true since their spherical extinction is modest, in which case  $R_* \sim R_{2/3}$ .

The incorporation of line blanketing necessitates one of several approximations, for which a ‘super-level’ approach is widely followed. Derived stellar temperatures depend sensitively upon the detailed inclusion of line-blanketing by iron-peak elements. In general, care must be taken when comparing [WC] stars to other CSPNe on the usual  $(T_{\text{eff}}, \log g)$  diagrams (e.g. Werner & Herwig 2006). Inferred bolometric corrections and stellar luminosities also depend upon detailed metal line-blanketing (e.g. Hillier & Miller 1999).

Until recently, the number of [WC] stars studied with non-LTE, clumped, metal line-blanketed models has been embarrassingly small, due to the need for detailed, tailored analysis of individual stars using a large number of free parameters. Exceptions include Todt, Gräfener, & Hamann (2006) for [WO] stars

and Crowther et al. (2003), Marcolino et al. (2007) for [WC] stars. Crowther, Morris & Smith (2006) presented a quantitative comparison between BD+30° 3639 ([WC9]) and HD 164270 (WC9) in effect confirming the qualitative result of Smith & Aller (1971), as illustrated in Fig. 2.

The majority of studies presented to date have focused upon optical spectral diagnostics, often supplemented by UV datasets. Herald & Bianchi (2004ab) have undertaken solely UV studies of Milky Way and LMC CSPNe including NGC 2371 ([WO]-PG1159) and SMP LMC 61 ([WC4]). In general we shall concentrate upon results from optical studies, since there may be potential systematic offsets from UV versus optical results (as is true for massive O stars).

#### 4. Wind properties

According to results from Leuenhagen et al. (1996), Leuenhagen & Hamann (1998) plus Koesterke & Hamann (1997ab), using a single stellar atmospheric code, late-type [WC8-10] stars possess uniformly lower wind velocities and stellar temperatures than early-type [WC4-5] and [WO] stars, as is the case for massive WC stars. Typically  $v_\infty = 200 - 1000 \text{ km s}^{-1}$  for late-type [WC] stars, with  $T_* = 30 - 80 \text{ kK}$  versus  $v_\infty = 1200 - 3500 \text{ km s}^{-1}$  and  $T_* = 125 - 150 \text{ kK}$  for early-type [WC] and [WO] stars.

Regarding mass-loss rates, late-type [WC] stars span a wide range i.e.  $\dot{M} \sim 10^{-6 \pm 0.5} M_\odot \text{ yr}^{-1}$ , neglecting wind clumping, while early-type [WC] stars possess stronger winds than [WO] stars, with  $10^{-5.8 \pm 0.3}$  and  $10^{-6.3 \pm 0.3} M_\odot \text{ yr}^{-1}$ , respectively. We will show that this difference is central to early-type stars being of either one flavour or another. Alternatively winds may be parameterized by a so-called transformed radius,  $R_t = R_*(v_\infty/M)^{4/3}$ .

It is now well established that massive WR stars are structured, as evidenced from the weakness of electron scattering wings with respect to recombination lines (Hillier 1991) and time variable profiles (Lépine et al. 2000; Grosdidier, Acker, & Moffat 2000). For a volume filling factor  $f (\leq 1)$ , actual mass-loss rates are a factor of  $1/\sqrt{f}$  lower than homogeneous models, although the current approach is highly simplified. Typically  $f \sim 0.1$  for both WC and [WC] stars, so actual mass-loss rates are a factor of  $\sim 3$  lower than homogeneous results.

#### 5. Elemental abundances

Late-type [WC] stars possess similar carbon-to-helium mass fractions to PG1159 stars, with typically  $X(\text{C}) \sim 50\%$  and  $X(\text{He}) \sim 40\%$ , in favour of the [WCL]  $\rightarrow$  [WCE]  $\rightarrow$  PG1159 sequence (Leuenhagen et al. 1996; Leuenhagen & Hamann 1998). However, most studies presented to date for early-type [WC] stars appear to show systematically *lower* carbon mass fractions of  $X(\text{C}) \sim 30\%$  and  $X(\text{He}) \sim 60\%$  (Koesterke & Hamann 1997ab; Todt et al. 2006). However, common abundance diagnostics are not feasible for very late-type [WC] stars (dominated by C II-III emission lines) and early-type [WC] stars (dominated by C IV and O V-VI lines). Indeed, based upon a narrower range of [WC] subtypes, based upon common diagnostics, Crowther et al. (2003) came to quite different conclusions, preferring no systematic differences in abundances between early-type

and late-type [WC] stars. Marcolino et al. (2007) also emphasised the difficulties in tightly constraining elemental abundances in [WC] stars.

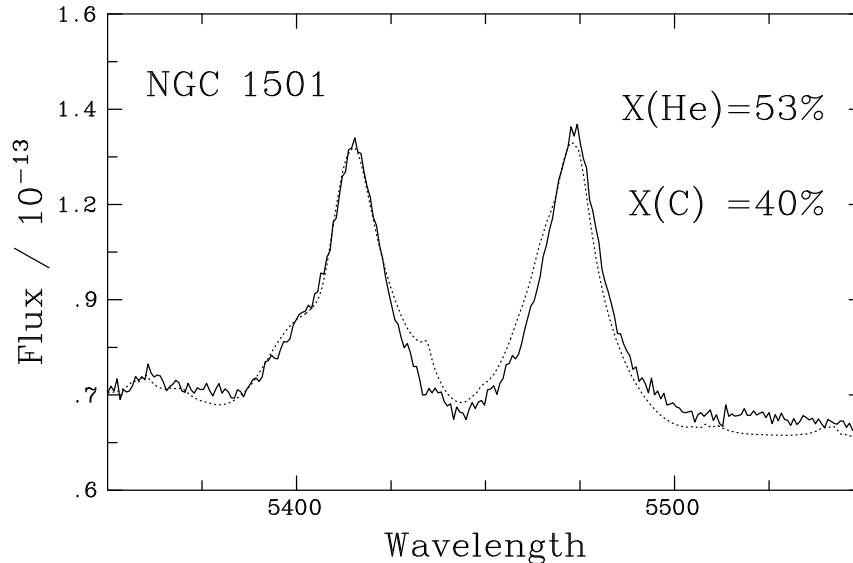


Figure 3. Representative fit (dotted lines) to He II 5411 and C IV 5471 lines (solid, WHT/ISIS) in NGC 1501, from which elemental abundances  $X(\text{He}):X(\text{C}):X(\text{O}) = 53:40:7\%$  are obtained.

Numerous oxygen diagnostics are available for [WC] and [WO]-type CSPNe, although these are highly sensitive to the precise oxygen ionization balance, so one should treat published abundances, typically  $X(\text{O}) \sim 10\%$ , as less reliable than helium or carbon. In [WC] stars, hydrogen has not been firmly established, although it can not be excluded in many CSPNe due to severe nebular contamination. There have been some claims for a non-zero hydrogen content, such as  $X(\text{H}) \leq 7\%$  by mass in He 2–113 ([WC10]) according to Leuenhagen et al. (1996) although this was established to be of nebular origin by De Marco, Barlow, & Storey (1997).

Overall H, He, C and O abundances (or limits) are consistent with a LTP scenario. If nitrogen is detected, a very late thermal pulse (VLTP) would be preferred (Werner & Herwig 2006). Due to the overwhelming carbon and oxygen emission line spectrum, the presence of nitrogen is however difficult to confirm. Marcolino et al. suggest  $X(\text{N}) \leq 0.1\%$  for all four [WC] stars, although Todt et al. (2006) propose  $X(\text{N}) \sim 1.5\%$  for PB6 ([WO]). Finally, Herwig, Langer, & Lugaro (2003) suggest neutron capture may be responsible for the partial conversion of Fe to other heavy elements. From UV spectral fits, Marcolino et al. (2007) suggest BD+30° 3639 is moderately Fe-deficient, with  $1/4 X(\text{Fe})_{\odot}$ . Abell 78 ([WO]-PG1159) and LMC SMP 61 ([WC4]) are also apparently Fe-deficient (Herald & Bianchi 2004ab).

## 6. New results for [WC] stars

In the light of apparently conflicting results, and the differences in subtype distributions of [WC]-type CSPN and massive WC stars (Fig. 1), a new study

of [WO], early- and late-type [WC] CSPNe has been undertaken. This is based upon a sample of 9 CSPNe, limited to flux calibrated optical spectroscopy from INT/IDS (NGC 6905, NGC 6751), WHT/ISIS (NGC 1501, M1-25, M2-43, NGC 40, He 2 459, BD+30° 3639) and AAT/RGO (Sand 3). It was necessary to employ flux calibrated spectroscopy to account for the underlying nebular continuum. In common with Todt et al. (2006) we adopt  $\log(L/L_\odot) = 3.7$  and a mass of  $0.6M_\odot$ . For the spectral analysis, the CMFGEN code is employed, for which line blanketing by He, C, O, Ne, Mg, Si, S, Ar, Ca, Fe and Ni are included (see Crowther et al. 2006 for details).

We have also re-examined the physical properties of CPD-56° 8032 ([WC10]) based on line blanketed models, and confirm the results of De Marco & Crowther (1998), adjusted for a clumped wind, with the exception that use of an extended C II model atom (P.J. Storey) suggests a lower mass fraction of X(He):X(C):X(O)  $\sim 50:30:20\%$ . Formally, we omit CPD-56° 8032 from our study given our desire to employ common abundance diagnostics for the entire sample.

Table 1. Physical and wind properties of Galactic Wolf-Rayet CSPNe, adopting  $\log(L/L_\odot) = 3.7$  ( $0.6 M_\odot$ ) and wind clumping with  $f = 0.1$ .

Subtype	$T_*$ kK	$R_{2/3}$ $R_\odot$	$\log \dot{M}$ $M_\odot \text{ yr}^{-1}$	$v_\infty$ $\text{km s}^{-1}$	Bol.Corr. mag	Sample
[WC10]	33	2.5	-6.0	225	-2.4	CPD-56° 8032
[WC9]	55-65	$0.8 \pm 0.15$	-6.1	700-1600	$-3.4 \pm 0.4$	BD+30° 3639 He 2-459
[WC8]	80-85	$0.45 \pm 0.05$	-6.3	950-1100	-4.0	NGC 40, M2-43
[WC4-5]	110-145	$0.3 \pm 0.15$	-6.3	1100-2350	$-4.7 \pm 0.5$	M1-25, NGC 6751
[WO1-4]	115-150	$0.16 \pm 0.04$	-7.0	1900-2500	$-6.4 \pm 0.2$	NGC 1501, NGC 6905, Sand 3

In common with previous studies we confirm increased stellar temperatures and wind velocities from [WC10] to [WC8-9] to [WC4-5], with again no significant differences between [WC4-5] and [WO1-4] stars, as indicated in Table 1. We conclude that the primary differences between [WC4-5] and [WO1-4] stars results from differences in mass-loss rate. After allowing for wind clumping, we find  $\dot{M} \sim 5 \times 10^{-7} M_\odot \text{ yr}^{-1}$  for [WC4-5] stars, versus  $1 \times 10^{-7} M_\odot \text{ yr}^{-1}$  for [WO1-4] stars. For massive WC and WO stars, earlier spectral types also follow from reduced wind densities for otherwise identical physical properties.

Crowther (1999) noted that *strong* winds cause *weak* O VI emission (WC4-5 subtypes) in hot carbon-rich WR stars as a result of recombination to lower ionization stages of oxygen in the optical line formation region ( $10^{11} \leq n_e \leq 10^{12} \text{ cm}^{-3}$ ). Conversely, *weak* winds permit *strong* O VI emission (WO subtypes) since oxygen does not recombine to lower ionization stages until lower electron densities. Emission lines from [WO]-type CSPN are typically narrower than for early-type [WC] stars for similar reasons, in the sense that winds have not yet

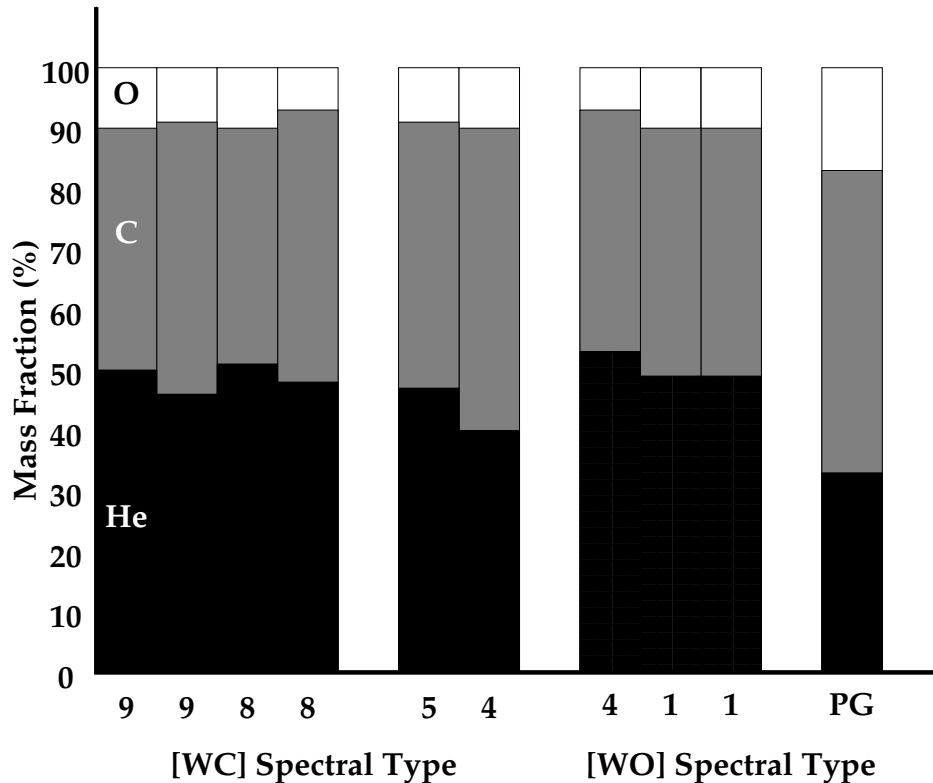


Figure 4. Elemental abundances for late- and early-type [WC] and [WO] stars from the present study, together with typical PG1159 star abundances (labelled PG). He, C and O mass fractions are shown in black, grey and white, respectively.

reached their maximum velocities in the optical line forming region of [WO] stars, in contrast to [WC] stars.

Wind densities of WR stars also affects the emergent ionizing flux distributions, in the sense that *soft* fluxes result from strong-lined stars with dense winds, with *hard* fluxes for weak-lined stars with lower density winds (Schmutz, Leitherer, & Gruenwald 1992; Smith, Norris, & Crowther 2002). Consequently, bolometric corrections for [WC] stars are functions of wind density as well as stellar temperature (Table 1). Use of appropriate spherical atmospheric models is relevant to photoionization models of [WC] stars, such as Ercolano et al. (2004) who made use of plane-parallel models for NGC 1501 ([WO4]).

For NGC 40 ([WC8]) and NGC 6905 ([WO4]) identical INT/IDS optical spectroscopy was used to the study of Marcolino et al. (2007). In general, differences in physical and wind properties are modest, with the exception of elemental abundances. We rely solely upon fits to He II 5411/C IV 5471 throughout (Hillier 1989), as illustrated in Fig. 3 for NGC 1501. Marcolino et al. choose to employ the whole spectral region for their abundance estimates, although this yields poor fits to these diagnostics in some instances. For Sand 3 ([WO1]) our results are intermediate between Todt et al. (2006) and recombination line



studies (Barlow & Hummer 1982), while both model atmosphere results differ from recombination line results in NGC 1501 ([WO4]), as illustrated in Table 2.

Table 2. Stellar elemental abundances for [WO] stars Sand 3 and NGC 1501 (by mass in %).

X(He)	X(C)	X(O)	Study
Sand 3			
38	54	8	Barlow & Hummer 1982
62	26	12	Todt et al. 2006
49	41	10	This study
NGC 1501			
36	48	16	Ercolano et al. 2004
55	35	10	Todt et al. 2006
53	40	7	This work

In common with Crowther et al. (2003) and Marcolino et al. (2007) we confirm no *systematic* difference between abundances in late-type and early-type [WC] and [WO] stars, as illustrated in Fig. 4. Regardless of the differences between our results and other studies, observations of the peak intensities of the He II 5411 and C IV 5471 across our sample favour a narrow range in elemental abundances.

## 7. Evolutionary connections with other H-deficient stars

If we adopt  $M = 0.6M_{\odot}$  for early-type [WC] and [WO] CSPNe together with the stellar radii inferred from  $T_*$  we obtain  $\log g \sim 6$ , versus  $\log g \sim 7$  for PG1159 stars. Overall, common abundances (recall Fig. 4), plus a continuum of decreasing wind strengths and increasing surface gravities from early-type [WC], [WO], [WO]-PG1159, and PG1159 suggests a direct evolutionary sequence, as illustrated in Fig. 5. Indeed, Longmore 4 (PG1159) has undergone a number of brief outbursts in which a modest increase in wind density caused a [WO]-PG1159 appearance (Bond, these proc.).

With regard to [WC8–9] stars, again adopting  $M = 0.6M_{\odot}$  together with the stellar radii inferred from  $T_*$  we obtain  $\log g \sim 4.5$ –5. Indeed, common abundances with [WC4–5] and [WO] CSPNe suggests an common evolutionary sequence, apart for the well-known gap between [WC8] and [WC5] in the subtype distribution for Galactic disk [WC]-type CSPNe (Fig. 1). Physically, little distinguishes the properties of such stars, with the exception of a modest decrease in wind density from [WC8] to [WC5], according to Crowther et al. (2002). This difference is almost certainly attributable to the higher surface gravities of CSPN with respect to their massive counterparts, resulting in substantially earlier subtypes on average. If we adopt the usual mass-luminosity relation for Galactic WC5–9 stars, we find  $\log g \sim 4.5$ –5 in all cases, such that spectral types are primarily due to subtle differences in wind density and stellar temperature.

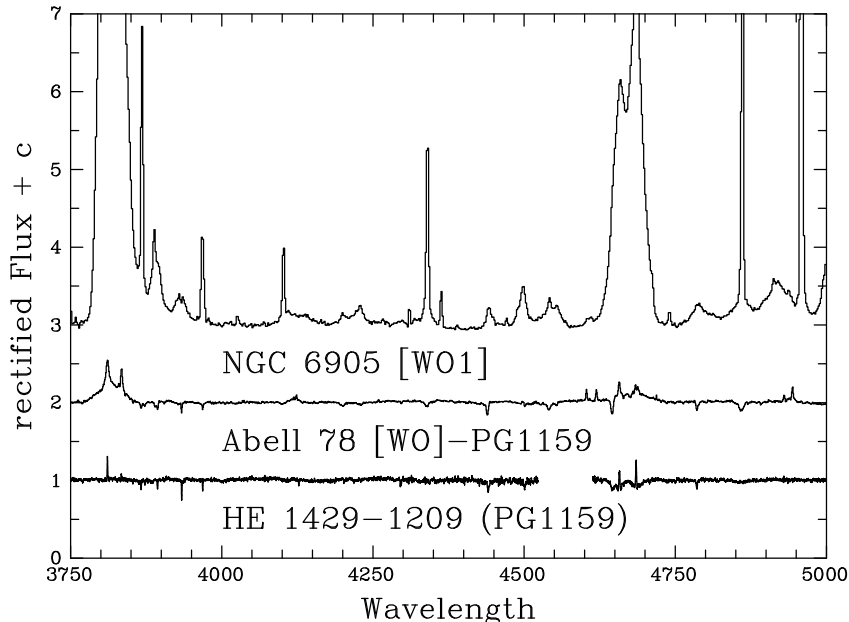


Figure 5. Spectral comparison between HE 1429–1209 (PG1159), Abell 78 ([WO]-PG1159) and NGC 6905 [WO1]. Derived elemental abundances are  $X(\text{He}):X(\text{C}):X(\text{O}) = 38:54:6, 54:37:8, 49:41:10\%$  respectively, according to Werner et al. (2004), Herald & Bianchi (2004a) and this work.

Indeed, weaker winds in massive LMC WC stars results in universal WC4 or WO spectral types (Crowther et al. 2002).

## 8. Summary

We discuss physical and wind properties of Wolf-Rayet CSPNe drawn from the recent literature plus new analyses for a range of subtypes. In general the higher ionization lines seen at earlier spectral type indicates an increased stellar temperature, although very early [WO] subtypes are favoured for hot CSPNe with weak winds, with [WC4–5] subtypes resulting for hot CSPNe with stronger winds. [WC8–9] subtypes correspond to lower temperature CSPNe with strong winds, with much lower temperatures indicated in [WC10] stars. We explain the differences in subtype distribution between Galactic disk CSPNe and massive WC stars as a result of decreased wind densities in the former, owing to increased surface gravities. Massive WC stars in the LMC differ from Galactic WC stars through reduced wind densities caused by lower metallicities, rather than increased surface gravities.

There does *not* appear to be a systematic difference between carbon-to-helium mass fractions in late to early-type CSPNe, at least for subtypes for which we are able to employ common diagnostics ([WC9] to [WO1]). Consequently, evolution from late-type [WC] through early-type [WC] and [WO] to PG1159 stars appears to be consistent with most abundance patterns, and expectations for a late thermal pulse. Indeed, we note that similar analysis tools have been

applied to the post He-flash system V605 Aql, which has now evolved through to a early-type [WC] spectral type over the past 80 years and shares a similar abundance pattern with  $X(\text{He}):X(\text{C}):X(\text{O}) = 54:40:5\%$  (Clayton et al. 2006).

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